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ABUNDANCES OF NEUTRON-CAPTURE ELEMENTS IN THE HOT EXTREME-HELIUM STARS V1920 CYGNI AND HD 124448[1]

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ABSTRACT

Analysis of *HST* STIS ultraviolet spectra of two hot extreme helium stars (EHes): V1920 Cyg and HD 124448 provide the first measurements of abundances of neutron-capture elements for EHes. Although the two stars have similar abundances for elements up through the iron-group, they differ strikingly in their abundances of heavier elements: V1920 Cyg is enriched by a factor of 30 in light neutron-capture elements (Y/Fe, Zr/Fe) relative to HD 124448. These differences in abundances of neutron-capture elements among EHes mirrors that exhibited by the R CrB stars, and is evidence supporting the view that there is an evolutionary connection between these two groups of hydrogen-deficient stars. Also, the abundances of Y and Zr in V1920 Cyg provide evidence that at least one EHe star went through a *s*-process synthesis episode in its earlier evolution.

Subject headings: stars: abundances – stars: chemically peculiar – stars: evolution

1. INTRODUCTION

Extreme helium stars (EHes) are carbon-rich B- and A-type supergiants in which surface hydrogen is merely a trace element (Jeffery et al. 1987). R CrB stars are similarly hydrogen-poor carbon-rich F- and G-type supergiants characterised by steep and irregular declines in visual brightness (Asplund et al. 2000). Understanding the origins of these rare luminous H-deficient stars remains a challenge. Detailed analyses of the star's chemical compositions hold clues to their origins. A significant lacuna presently exists: the abundances of neutron-capture elements in EHes are unknown. Here, we provide and comment on the first estimates of these abundances for a pair of EHes.

Two scenarios are contenders to account for the EHes and the R CrB stars: the merger of a He white dwarf with a C-O white dwarf (Webbink 1984), and a final shell flash in a post-AGB star on the white dwarf cooling track (Iben et al. 1983). A final shell flash appears most likely responsible for the remarkable stars FG Sge (Langer, Kraft & Anderson 1974; Gonzalez et al. 1998) and V4334 Sgr (Sakurai's object – Duerbeck & Benetti 1996; Asplund et al. 1997) with R CrB-like light curves, high overabundances of the neutron-capture elements, and probable or certain H-deficiency. White dwarf mergers appear to account for the compositions of EHes and (probably) the R CrBs (Pandey et al. 2001; Saio & Jeffery 2002; Asplund et al. 2000). The *s*-process abundances in EHes are crucial clues because, in the merger model, enrichment of neutron-capture elements is not expected unless some *s*-processing occurs during the merger (Pandey et al. 2001).

For hot EHes ($T_{\rm eff} > 14000$ K), the lighter neutron-capture elements (Sr, Y, Zr) and the heavier elements (Ba and the lanthanides) are undetectable in optical spectra because ionization equilibrium ensures that the dominant ion is X^{2+}, whose strongest lines are principally in the ultraviolet. Fortunately, the EHes have appreciable ultraviolet flux and are observable at high-spectral resolution with the *Hubble Space Telescope's* Space Telescope Imaging Spectrograph. Here, we report abundance analyses for a pair of hot EHes of similar temperature and gravity and with almost identical compositions except for abundances of Y and Zr.

2. OBSERVATIONS

Ultraviolet: V1920 Cyg (aka HD 225642 and LS II +33 5) and HD 124448 were observed (program ID: GO 9417) on 2002 October 18 and 2003 July 21, respectively, with the *HST*'s STIS Near-UV/MAMA, using the E230M grating and $0.''2 \times 0.''06$ aperture, which provides a resolving power ($\lambda/\Delta\lambda$) of 30,000. Two spectra for each star were obtained: V1920 Cyg (Data Sets O6MB06010 and O6MB06020 with exposure times 1844 s and 2945 s, respectively) and HD 124448 (Data Sets O6MB02010 and O6MB02020 with exposure times 1977 s and 3054 s, respectively). The spectrum covered the wavelength range from 1840Å to 2670Å. Since the absorption profiles are broad for V1920 Cyg (projected rotational velocity $v\sin i \sim 40$ km s^{-1}; Jeffery et al. 1998) and HD 124448 ($v\sin i \sim 20$ km s^{-1}; Schönberner & Wolf 1974), the coadded spectra from two exposures were rebinned to a lower resolution to improve the signal-to-noise (S/N) ratio, which is about 100 at 2500Å. The resulting spectra have a resolving power of 7500 (V1920 Cyg) and 15000 (HD 124448).

Optical: A high-resolution optical spectrum of V1920 Cyg was obtained on 1996 July 25 at the W. J. McDonald Observatory's 2.7-m telescope with the coudé cross-dispersed echelle spectrograph (Tull et al. 1995) at a resolving power of 60,000. The observing procedure, the detector, and the wavelength coverage are as described in Pandey et al. (2001).

3. ABUNDANCE ANALYSIS

Model atmospheres from the code STERNE and synthetic spectra computed with the Belfast LTE code SPECTRUM are combined in the analysis (Jeffery, Woolf, & Pollacco 2001). Input parameters for STERNE including the composition were taken from previous abundance analyses. These parameters are the effective temperature $T_{\rm eff}$ = 16180±500 K, the surface grav-

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ity log g = 2.00±0.25 (cgs units), the microturbulent velocity ξ = 15±5 km s^{-1}, and the abundance ratio C/He = 1% by number of atoms for V1920 Cyg (Jeffery et al. 1998), and $T_{\rm eff}$ = 15500±800 K, log g = 2.10±0.20 (cgs units), ξ = 10 km s^{-1}, and C/He = 1% for HD 124448 (Schönberner & Wolf 1974; Heber 1983). Derived abundances are sufficiently close to the input values that iteration is unnecessary. The continuous opacity is dominated by photoionization of neutral helium and electron scattering with electrons supplied by helium. In this situation, the He I line strengths are insensitive to the abundances of the trace elements, and to $T_{\rm eff}$, but are sensitive to gravity because the strong lines have Stark-broadened wings. The adopted models satisfactorily reproduce the optical and ultraviolet He I line profiles (V1920 Cyg). The derived abundances (Table 1) from spectum syntheses are given as $\log\epsilon$(X) and normalized with respect to total mass where $\log\Sigma\mu_X\epsilon$(X) = 12.15 with μ as the atomic weight.

TABLE 1
Chemical Abundances in two hot EHes

			V1920 Cyg		
Species	Z	Solar[a]	Optical	UV	HD 124448
H I	1	12.00	<6.2(Hα)	···	···
He I	2	10.98	11.5(4)	11.5(1)	···
C II	6	8.46	9.6±0.2(8)	9.7±0.1(3)	9.4±0.1(1)
N II	7	7.90	8.6±0.3(7)	···	···
O II	8	8.76	9.6±0.2(2)	···	···
Mg II	12	7.62	7.7±0.2(1)	7.8±0.2(1)	7.7±0.2(1)
Si II	14	7.61	···	7.1±0.3(1)	6.9±0.3(1)
S II	16	7.26	7.3±0.2(5)	···	···
S III			7.1±0.1(3)	···	···
Mn II	25	5.58	···	4.6±0.3(1)	4.7±0.3(1)
Mn III			···	5.0±0.2(4)	4.8±0.2(4)
Fe II	26	7.54	···	6.8±0.3(10)	7.0±0.3(10)
Fe III			7.0±0.3(4)	6.8±0.1(4)	7.2±0.1(4)
Co II	27	4.98	···	4.6±0.3(1)	4.6±0.3(1)
Ni II	28	6.29	···	5.6±0.3(2)	5.6±0.3(3)
Zn II	30	4.70	···	4.6±0.3(1)	4.2±0.3(1)
Sr II	38	2.99	<4.3	···	···
Y III	39	2.28	···	3.1±0.3(3)	1.8±0.3(1)
Zr III	40	2.67	···	3.6±0.2(8)	2.6±0.2(3)
La III	57	1.25	···	<2.2	···
Ce III	58	1.68	···	<2.0	<1.5
Nd III	60	1.54	<1.8	···	···

[a]Recommended solar system abundances from Table 2 of Lodders (2003).

The adopted gf-values were taken from the NIST database[5] for H, He, Mg, Si, S, Mn II, Co, Ni, Zn, and Sr, Wiese, Fuhr & Deters (1996) for C, N, and O, and Kurucz's database[6] for Mn III and Fe III. For Zr III, three sets of theoretical gf-values are in good agreement: Redfors (1991), Reader & Acquista (1997), and Charro, López-Ayuso & Martín (1999). We adopt Redfors (1991) gf-values with the suggested correction by Sikström et al. (1999) for Y III and Zr III; the estimated uncertainty in the gf-values is reported to be within 10%. The gf-values for La III, Ce III, and Nd III are from DREAM database[7], Biémont, Quinet & Ryabchikova (2002), and Zhang et al. (2002), respectively. The estimated abundance uncertainty is followed in brackets by the number of useful lines. The uncertainty is the combined uncertainty from the estimated errors in the atmospheric parameters or, if larger, the line-to-line scatter in the abundances. Note that for the ultraviolet spectra, the same lines were generally used for both stars and, hence, the abundance ratios between the stars are independent of the adopted gf-values.

Several consistency checks were applied to our analyses, especially to the more complete analysis of V1920 Cyg. Ionization equilibrium for Fe II/Fe III is satisfied for both stars, and for S II/S III for V1920 Cyg. Excitation equilibrium is found for the Fe III optical lines for V1920 Cyg; the ultraviolet lines used in our analyses do not offer a range in their lower excitation potential. When an element provides lines in the optical and the ultraviolet spectra of V1920 Cyg, the abundances are in good agreement. Our results for V1920 Cyg are in good agreement with those by Jeffery et al. from a lower resolution optical spectrum of limited bandpass. The agreement for HD 124448 is less good between our ultraviolet-based abundances and those from a photographic optical spectrum (Heber 1983). Our limit on the H abundance for V1920 Cyg from the absence of the Hα line is more than 2 dex less than the abundance offered by Jeffery et al. from the Hβ line. Heber (1983) put the H abundance of HD 124448 at $\log\epsilon$(H) $<$ 7.5.

4. NEUTRON-CAPTURE ELEMENTS

Our optical and ultraviolet spectra of hot EHes were scanned for lines of Y III, Zr III, and of the doubly-ionized lanthanides. Inspection of the ultraviolet spectra showed that the two EHes differ dramatically in the abundances of Y and Zr. This point is highlighted by Figure 1. In Figure 1a, the Zr III line at 2656.47 Å is comparable in strength to the Mg II lines at 2660.8 Å in V1920 Cyg (lower spectrum) but in HD 124448 the Zr III line is extremely weak. Figure 1b shows a similar, albeit less dramatic comparison on account of blends, for the Y III line at 2367.2 Å. These differences are not attributable to differences in stellar parameters. This comparison eliminates the possibility that the lines which we attribute to Y III and Zr III are merely unidentified lines of iron or other more abundant species.

The measured wavelengths of Y III and Zr III lines were taken from Epstein & Reader (1975) and Khan, Chaghtal & Rahimullah (1981), respectively. The Y III resonance lines at 2414.60, 2367.23, and 2327.31Å are detected in the spectrum of V1920 Cyg with the 2367.23Å line seen as a contributor to a blended line in the spectrum of HD 124448 (Figure 1). Lines of Zr III at 2664.27, 2656.47, 2643.82, 2620.56, 2593.70, 2102.26, 1921.94, and 1863.98Å in the spectrum of V1920 Cyg were used to set the abundance. Three of the Zr III lines at 2664.27, 2656.47, and 2643.82Å were detectable in the spectrum of HD 124448.

Figure 1 shows our syntheses of the region around 2656.47 Å. A small change in the assumed Fe abundance between V1920 Cyg ($\log\epsilon$(Fe) = 6.8) and HD 124448 ($\log\epsilon$(Fe) = 7.1) is recognized.

An upper limit to the Sr abundance for V1920 Cyg is estimated from the non-detection of the resonance line of Sr II 4215.52Å.

An unsuccessful search was conducted for the doubly-ionized lanthanides. We mention here only those lanthanides

[5] http://physics.nist.gov/cgi-bin/AtData/lines_form
[6] http://kurucz.harvard.edu
[7] ftp://mail.umh.ac.be/pub/ftp_astro/dream/LaIII

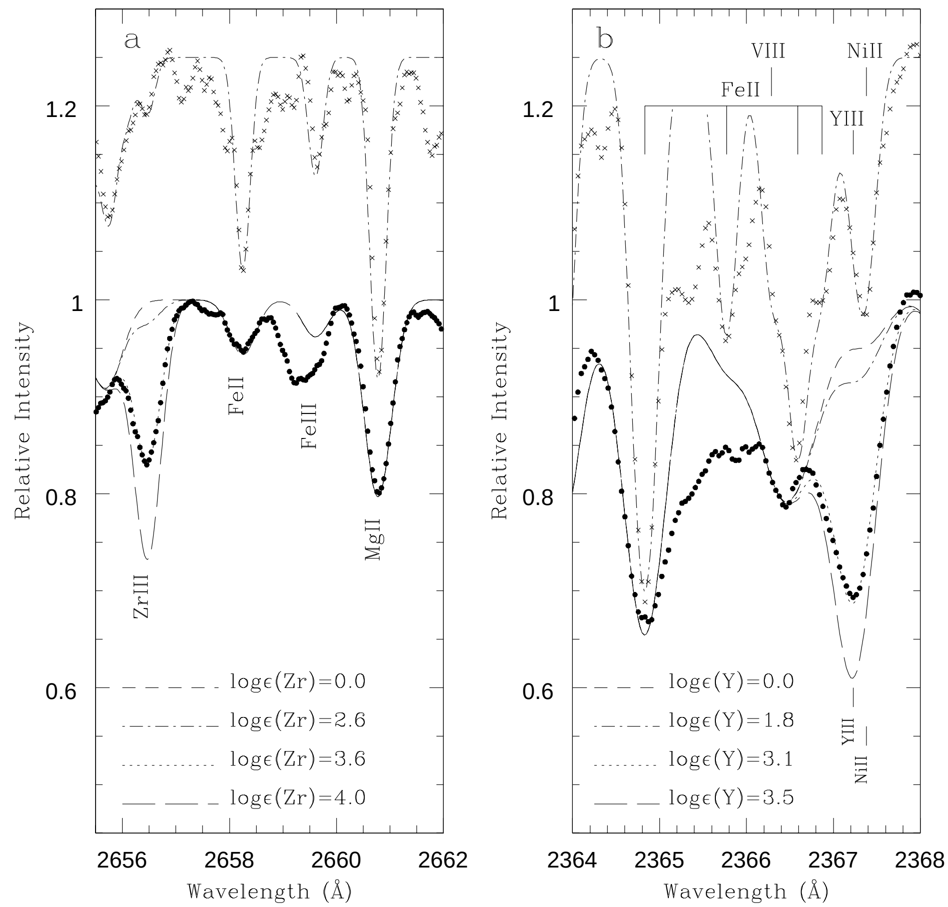

FIG. 1.— The observed spectra of V1920 Cyg and HD 124448 are represented by filled circles and crosses, respectively. Panel-a shows the region including the Zr III line at 2656.5Å. Synthetic spectra for four different Zr abundances are shown for V1920 Cyg with log ϵ(Zr) = 3.6 providing a satisfactory fit to the observed line. The abundance log ϵ(Zr) = 2.6 provides a fit to the sharper line in the HD 124448 spectrum. Panel-b shows the region including the Y III line at 2367.2Å which is blended with a Ni II line. The synthetic spectrum with log ϵ(Y) = 3.1 provides a fit to V1920 Cyg's spectrum, and log ϵ(Y) = 1.8 to HD124448's spectrum. In each Panel, principal lines are identified.

providing significant upper limits to the abundances. A La III 2379.37Å resonance line provides the upper limit for V1920 Cyg. An upper limit to the Ce abundance is obtained by comparing the synthetic and observed profile of the low excitation Ce III 2603.59Å line. The two strongest resonance lines of Nd III at 5193.06Å and at 5294.10Å set the upper limit to the Nd abundance in V1920 Cyg.

5. DISCUSSION

Our abundance analysis of optical and ultraviolet spectra of V1920 Cyg confirms the results obtained by Jeffery et al. (1998) for elements from C to the iron-group. We extend the earlier analysis to Mn, Co, Ni, and Zn, and, in particular, to the neutron-capture elements Y and Zr. We similarly confirm and extend the previous analyses of HD 124448 (Schönberner & Wolf 1974; Heber 1983). We have provided the first, abundances of neutron-capture elements for hot EHes. These neutron-capture element abundances suggest that at least in the EHe star V1920 Cyg, *s*-process nucleosynthesis did occur in its earlier evolution.

An interesting similarity is suggested by these abundances and those of the R CrBs. A feature of the R CrB stars is the large star-to-star variation in the abundances of the neutron-capture elements. For 'majority' R CrBs (Lambert & Rao 1994), [Y/Fe] and [Zr/Fe] ranges from +0.3 to about +1.6 but with smaller values for [Ba/Fe], [La/Fe], and presumably other lanthanides (Asplund et al. 2000). This range and the non-solar ratio of Y and Zr to Ba and lanthanides was confirmed by Rao & Lambert (2003) from a differential analysis of the newly discovered R CrB star V2552 Oph and R CrB. Among 'minority' R CrBs (i.e., very Fe-poor stars), somewhat more extreme values are known with a similar contrast between light and neutron-capture elements. The cool peculiar R CrB U Aqr has very extreme neutron-capture element enrichments: [Y/Fe] = +3.3 and [Ba/Fe] = +2.1 (Vanture, Zucker & Wallerstein 1999; also Bond, Luck & Newman 1979). Limited data for cool EHes suggest Sr, Y, or Zr abundances within the R CrB range, say [X/Fe] of 0.0 to +0.9 (Pandey et al. 2001).

Our STIS spectra demonstrate that the star-to-star variation in [Y/Fe] and [Zr/Fe] among hot EHes is at least as great as among the 'majority' R CrB stars: V1920 Cyg with [Y/Fe] $\simeq$ [Zr/Fe] $\simeq$ 1.6 is at one end of the range and HD 124448 with [Y/Fe] $\simeq$ [Zr/Fe] $\simeq$ +0.1 is at the other end. Unfortunately, the upper limits set on abundances of lanthanides do not permit us to check that EHes follow R CrBs in showing smaller enrich-

ments of these heavier elements. The upper limits set for Ce and Nd in V1920 Cyg ([Ce/Fe] $\leq$+1.1 and [Nd/Fe] $\leq$+1.0) hint at a behavior similar to the R CrBs.

As noted in the Introduction, two scenarios are potential sources of H-deficient luminous stars. A final-flash in a post-AGB stars, and a merger of a He with a C-O white dwarf. The C and O abundances of the hot EHes are consistent with predictions of white dwarf mergers but not the current final-flash models (Pandey et al. 2001; Saio & Jeffery 2002). Saio & Jeffery (2002) also show that a EHe star formed by accretion of He-rich material by a C-O white dwarf has the pulsational properties of real EHe stars. Additionally, a merger better accounts for large line widths seen in spectra of EHes; the accreting star is spun up by the accreted gas from the (former) orbiting He white dwarf. Yet, the neutron-capture element abundances of the EHes are, perhaps, more readily explained by the final-flash scenario, as suggested by the final-flash candidates FG Sge and V4334 Sgr with neutron-capture element overabundances. The range in relative overabundances of Y and Zr to Ba and the lanthanides varies greatly between the pair: V4334 Sgr has a high relative overabundance (Asplund et al. 1997), but FG Sge has a low relative overabundance (Gonzalez et al. 1998).

Enrichment of neutron-capture elements is not expected for the EHes unless synthesis by neutrons via the *s*-process occurs during the merger (Pandey et al. 2001). The surface of the C-O white dwarf, the former core of an AGB star, will be rich in *s*-process products but little of this C-rich material is required at the surface of the star after accretion of He-rich material to account for the observed abundances of the light elements. A thin residual He-shell around the C-O white dwarf core could contribute *s*-process products. The He white dwarf and its possible H-rich skin are not expected to be rich in neutron-capture elements. One supposes that accretion of the He white dwarf may be accompanied by an episode of nucleosynthesis including release of neutrons through $^{13}C(\alpha,n)^{16}O$ with ^{13}C created by H-burning. If, as seems plausible, the strength of the neutron source and efficiency of neutron captures varies from merger to merger, the range in the neutron-capture element abundances, as seen here for the EHe pair V1920 Cyg and HD 124448 and known among R CrBs, results. Aspects of the composition of the minority R CrBs suggest nucleosynthesis may accompany the accretion of He-rich material by the C-O white dwarf. Theoretical studies of the merger scenario are to be sought with careful examination of the attendant nucleosynthesis.

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